

The fraction of type Ia supernovae exploding inside planetary nebulae (SNIPs)

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ABSTRACT

Using three independent directions we estimate that the fraction of type Ia supernovae (SNe Ia) exploding inside planetary nebulae (PNe), termed SNIPs, is at least $\sim 20\%$. Our three directions are as follows. (i) Taking the variable sodium absorption lines in some SN Ia to originate in a massive circumstellar matter (CSM), as has been claimed recently, we use the results of Sternberg et al. (2014) to imply that $\gtrsim 20\%$ of SN Ia occur inside a PN (or a PN descendant), hence classify them as SNIPs. (ii) We next use results that show that whenever there are hydrogen lines in SN Ia the hydrogen mass in the CSM is large $\gtrsim 1M_{\odot}$, hence the explosion is a SNIP. We make the simplest assumption that the probability for explosion is constant in time for up to about 10^5 yrs after the merger of the core with the white dwarf (WD) in the frame of the core-degenerate scenario. This results with at least few $\times 10\%$ of SNe Ia that may have a SNIP origin. (iii) We examine the X-ray morphologies of 13 well-resolved close-by SN remnants (SNRs) Ia and derive a crude upper limit, according to which 10–30% of all SNRs Ia possess opposite ear-like features, which we take as evidence of SNIP origin. Our results, together with several other recent results, lead us to conclude that the two scenarios most contributing to SNe Ia are the core degenerate and the double degenerate scenarios. Together these two account for $> 95\%$ of all SNe Ia.

Subject headings: ISM: supernova remnants — supernovae: stars: binary — planetary nebulae: general

1. INTRODUCTION

It is agreed that Type Ia supernovae (SN Ia) are thermonuclear explosions of white dwarfs (WDs) accompanied by a complete destruction of the WD, or at least one of the two

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interacting WDs (e.g. Maoz et al. 2014). On the other hand, there is no consensus yet on the evolutionary route of the exploding WD. The different scenarios discussed in the literature in recent years can be classified according to different criteria, one of which is summarized in Table 1.

We list in Table 1 the relevant observational properties of each scenario that might be compatible with the presence of Ears, or on the contrary be in conflict with the presence or Ears. We also list what we consider as main predictions, strong characteristics, and main difficulties of each scenario, as these can be relevant to the properties related to Ears. For example, the presence of massive, approximately $1M_{\odot}$ of CSM in the Kepler SNR, poses a problem to several scenarios, such as the massive CSM inferred in the SN Ia PTF11kx. All scenarios suffer from difficulties, but we find that three scenarios suffer from severe difficulties, making them highly unlikely to be the main evolutionary route of SN Ia. As all scenarios have difficulties, we list them and discuss them in alphabetical order.

(a) *The core-degenerate (CD) scenario* (e.g., Sparks & Stecher 1974; Livio & Riess 2003; Kashi & Soker 2011; Soker 2011; Ilkov & Soker 2012, 2013; Soker et al. 2013). Within this scenario the WD merges with the hot core of a massive asymptotic giant branch (AGB) star. In this case the explosion might occur shortly or a long time after merger. By shortly we refer to a time scale within which the SN ejecta will interact with gas originated from the earlier phases of the progenitors, e.g., the ejected common envelope (CE). By a long time we refer to a time when any mass lost from the progenitor has dispersed in the ISM. The limit is not sharp, but it is typically $\sim 10^5 - 10^6$ yr.

(b) *The double degenerate (DD) scenario* (e.g., Webbink 1984; Iben & Tutukov 1984). This scenario is based on the merger of two WDs. However, this scenario does not specify the subsequent evolution, namely, how long after merger does the explosion of the remnant take place (e.g., van Kerkwijk et al. 2010). Recent papers, for example, discuss violent mergers (e.g., Lorén-Aguilar et al. 2010; Pakmor et al. 2013; Aznar-Siguán et al. 2013) as possible channels of the DD scenario. This seems very problematic as it leads to a highly non-spherical supernova remnant (SNR; Pakmor et al. 2012), while Lopez et al. (2009) find that SNRs Ia generally possess a spherical structure. Others consider very long delays from merger to explosion, e.g., because rapid rotation keeps the structure overstable (Piersanti et al. 2003; Di Stefano et al. 2011; Justham 2011; Ilkov & Soker 2012; Tornambé & Piersanti 2013). The upper limit on the size of the progenitor of SN 2011fe (e.g., Nugent et al. 2011; Bloom et al. 2012; Piro & Nakar 2014) implies that the exploding object was very compact, ruling out the presence of close gas. Since the merger process ejects gas, the DD scenario is limited to have explosion at a time of $\gg 10$ yr after merger (Levanon et al. 2014). As well, the production of manganese (Seitenzahl et al. 2013) and

Table 1: Confronting five SN Ia scenarios with observations

Scenario ^[1]	Core Degenerate	Double Degenerate	Double Detonation	Single Degenerate	WD-WD collision
Presence of 2 opposite Ears in some SNR Ia.	Explained by the SNIP mechanism (studied in this paper).	Low mass Ears if jets during merger (Tsebrenko & Soker 2013).	No Ears are expected for He WD companion.	Ears by jets from accreting WD (Tsebrenko & Soker 2013).	No Ears are expected
$\approx 1M_{\odot}$ CSM in Keplers SNR	The massive CSM shell might be a PN.	No CSM shell	Any CSM is of a much lower mass	Can be explained by heavy mass loss from an AGB donor. ^[5]	No CSM shell
Main Scenario Predictions	1. Single WD explodes 2. Massive CSM in some cases (SNIP)	1. Sufficient WD-WD close binaries 2. DTD $\propto t^{-1}$	1. Asymmetrical explosion 2. $M_{WD} < 1.2M_{\odot}$	1. Companion survives 2. $M_{WD} \simeq M_{Ch}$	Asymmetrical explosion
General Strong Characteristics	1. Explains some SN Ia with H-CSM 2. Symmetric explosion	Explains very well the delay time distribution (DTD)	Ignition easily achieved	1. Accreting massive WDs exist 2. Many explosions with $\sim M_{Ch}$	1. Ignition easily achieved 2. compact object
General Difficulties	More work on 1. Ignition process 2. DTD 3. Merge during CE 4. Find massive single WDs	1. Ignition process 2. Inflated gas around merger product ^[2] 3. Asymmetrical explosion	Ejected He in some sub-scenarios	1. Cannot account for DTD 2. CSM of PTF 11kx too massive	Does not reproduce the DTD at $t < 0.4$ Gyr
Severe Difficulties			1. $M_{WD} < 1.2M_{\odot}$ 2. Highly asymmetrical explosion	1. Not enough systems 2. Companions not found 3. No hydrogen observed	1. Can account for $< 1\%$ of SN Ia 2. Highly asymmetrical explosion ^[3]
Fraction of SN Ia	$> 20\%$ (this work)	$< 80\%$ (this work)	$< \text{few} \times \%$ (Piersanti et al. 2013) ^[3]	0%	$< 1\%$ (Soker et al. 2014) ^[4]

Notes:

¹Scenarios for SN Ia by alphabetical order; see text for details.

²Disk originated material (DOM) around the merger product rules out explosion within several $\times 10$ yr of merger (Levanon et al. 2014). Such a late explosion will solve also the asymmetrical SNR problem.

³See also Papish et al. (2015).

⁴See Section 2 in first version of astro-ph (arXiv:1309.0368v1) of Soker et al. (2014)

⁵ In some respects the formation of a shell with Ears in the SD scenario with an AGB star as the donor is similar to that in the CD scenario, as both are results of mass loss from an AGB star.

nickel that requires exploding WDs close to the Chandrasekhar mass can be explained in the DD scenario if there is enough time for the merging WDs to coalesce to a massive remnant.

The DD and the CD scenarios can overlap in the sense that if the merger occurs after the termination of the CE phase, but while the core is not yet on the cooling track of a WD, both scenarios comprise the system. Basically, the scenarios can overlap if the merger occurs during the planetary nebula phase of the system. However, there are two significant differences between the two scenarios. In the DD scenario the merger is of two cool WDs, while in the CD scenario it is a WD with a hot core. In the DD scenario the delay to explosion is mainly due to gravitational waves emitted by the two WDs (e.g., review by Maoz et al. 2014), while in the CD scenario it is due to angular momentum loss by the merger remnant (Ilkov & Soker 2012). One significant difference between the two scenarios is that due to the long time scale of gravitational waves, no massive circumstellar matter (CSM) is expected around the exploding star in the DD scenario. On the other hand, in the CD scenario a large fraction of SN Ia will possess a CSM that will influence the spectrum of the SN and/or the morphology of the SNR. Since in the CD scenario this CSM was ionized at some time by the central WD remnant of the merger, it was a planetary nebula (PN). Such SNe Ia inside PNe, or remnants of PNe, are termed SNIPs (Tsebrenko & Soker 2015).

(c) *The double-detonation (DDet) mechanism* (e.g., Woosley & Weaver 1994; Livne & Arnett 1995). Here a sub-Chandrasekhar mass WD accumulates a layer of helium-rich material coming from a donor. The helium layer is compressed as more material is accreted and detonates, leading to a second detonation near the center of the CO WD (Shen et al. 2013 and references therein). There are two types of He WD companions: A WD of mass $\sim 0.4 - 0.45 M_{\odot}$ residing at $\sim 0.02 - 0.03 R_{\odot}$ from the exploding CO WD (Guillochon et al. 2010; Raskin et al. 2012; Pakmor et al. 2013), or a lighter, $\sim 0.2 M_{\odot}$, WD at an orbital separation of $\sim 0.08 R_{\odot}$ (Bildsten et al. 2007; Shen & Bildsten 2009). Piersanti et al. (2013) found that the DDet scenario can account for only a small fraction of all SN Ia, but Ruiter et al. (2011) found a much larger fraction that can be attributed to the sub-Chandrasekhar DDet scenario. Papish et al. (2015) found that the explosion leads to a non-spherical SNR, and in a case of a close helium WD, the latter will be ignited and will eject helium. As elaborated in Papish et al. (2015), the expected SNR has a dipole asymmetry that no well resolved SNR Ia has. For example, although SN1006 has a dipole asymmetry, Papish et al. (2015) find this dipole to be different from the one expected due to the effect of the He WD companion on the ejecta in the DDet scenario. Another problem with this scenario is that because the exploding CO WD almost does not grow before it explodes (Shen & Bildsten 2009), it predicts that most exploding WDs will have a mass of $< 1.2 M_{\odot}$. This is in odd with recent findings that most SN Ia masses are peaked around $1.4 M_{\odot}$ (Scalzo et al. 2014). Seitenzahl et al. (2013) also claim that at least 50% of all SN Ia come from near Chandrasekhar mass (M_{Ch})

WDs. We conclude that the DDet scenario can lead to explosions similar to SN Ia, but not to the common SN Ia.

(d) *The single degenerate (SD) scenario* (e.g., Whelan & Iben 1973; Nomoto 1982; Han & Podsiadlowski 2004). In this scenario a white dwarf (WD) accretes mass from a non-degenerate stellar companion and explodes when its mass reaches the Chandrasekhar mass limit. The search for companions to SNe Ia came with null results (e.g. Kerzendorf et al. 2013, 2014) and made this scenario very unlikely. Another grave difficulty is that population synthesis studies find that the SD scenario can account for only a small fraction of SN Ia (e.g., Ruiter et al. 2011; Toonen et al. 2013; Claeys et al. 2014). We note that Hachisu et al. (2012) who included delay detonation due to WD spin-up, on the other hand, argue that the SD scenario can produce the required number of SNe Ia, and the observed delay time distribution. A very interesting set of observations is the detection of CSM from hydrogen lines (e.g., Silverman et al. 2013; Fox et al. 2014) and sodium absorption lines (Maguire et al. 2013; Sternberg et al. 2014) in some SN Ia. These have been used to argue for the SD scenario (e.g., Dilday et al. 2012 and Silverman et al. 2013 from hydrogen, and Patat et al. 2007 and Sternberg et al. 2011 from sodium). However, it seems that the CSM mass inferred both from hydrogen, as in PTF 11kx (Soker et al. 2013), and from sodium absorption lines (Soker 2014), is too large to be accounted for by the SD scenario. Instead, Soker et al. (2013) and Soker (2014) strongly argue that the CD scenario best accounts for these observations.

(e) *The WD-WD collision scenario* (e.g., Raskin et al. 2009; Rosswog et al. 2009; Thompson 2011; Katz & Dong 2012; Kushnir et al. 2013). In this scenario two WDs collide and immediately ignite. The collision is most likely induced by a tertiary star (Katz & Dong 2012) by the Lidov-Kozai mechanism (Lidov 1962; Kozai 1962). Despite some attractive features of this scenario, it can account for at most few per cent of all SNe Ia (Hamers et al. 2013; Prodan et al. 2013; Soker et al. 2014). Another problem is that the explosion in most cases is highly non-spherical, contradicting the observed morphology of most young close-by SNRs. A third problem might be the delay time distribution (DTD) that behaves as $\propto t^{-1}$ (e.g., Graur & Maoz 2013). Although the WD-WD collision scenario can lead to the observed $\propto t^{-1}$ DTD, it does so only at late times after star formation, > 0.4 Gyr according to Hamers et al. (2013). The fraction of systems that might be explained by the WD-WD collision is $< 1 - 2\%$ of all SN Ia (Hamers et al. 2013).

Based on the discussion above we consider the CD and DD scenarios as the most likely scenarios to account for most or all SN Ia. In this paper we try to set a lower limit on the fraction of SN Ia that come from the CD scenario by considering the influence of the CSM on the SN spectra (Section 2) and on the morphology of SNRs (Section 3). Our short summary is in Section 4.

2. SN Ia WITH CIRCUMSTELLAR MATTER

2.1. Sodium absorption lines

Sternberg et al. (2014) find that $19 \pm 12\%$ of SN Ia in star-forming galaxies exhibit time-variable sodium features associated with circumstellar material. Maguire et al. (2013) obtain a similar result, showing that $\sim 20\%$ of SNe Ia possess blueshifted narrow Na I D absorption features compared to non-blueshifted Na I D features.

Some papers (e.g., Patat et al. 2007, 2011; Sternberg et al. 2011) attributed the Na I D absorption lines to a wind from a giant star in the SD scenario. However, it seems that the CSM that supplies the sodium is too massive to be accounted for in the SD scenario (Soker 2014). Instead, Soker (2014) suggested that the sodium comes from dust in a $\sim \text{few} \times M_{\odot}$ shell. This Na-from-dust absorption (NaDA) model better fits the CD scenario where the shell is the mass that was ejected in the common envelope (CE) process (assuming it is not ISM).

For absorption lines to appear, the CSM should reside along the line of sight. Since in many cases the CSM might not cover the entire sphere, the $19 \pm 12\%$ is a lower limit. On the other hand, in some cases the absorbing gas might be of ISM origin. Overall, the study of Sternberg et al. (2014), within the frame of the NaDA model, suggests that $> 20\%$ of SN Ia have massive CSM that qualifies them as SNIP candidates. We note that Shen et al. (2013), in the frame of the DDet scenario, and Raskin & Kasen (2013), within the frame of the DD scenario, have also attempted to explain the presence of CSM around some SNe Ia. The CSM mass in these models is too low for the NaDA model (Soker 2014), although can be sufficient for other explanations for the Na absorption lines, e.g. Patat et al. (2007) and Chugai (2008).

Interestingly, all the SN Ia that show time-variable sodium features reside in star-forming galaxies (Maguire et al. 2013). This suggests that either the absorbing gas is of ISM origin, as dense clouds are abundant in star forming galaxies, or that the progenitors of these systems are relatively massive stars, $M \gtrsim 3 - 4M_{\odot}$ that evolve rapidly. We assume that the time-variable sodium features are due to CSM as in that case the CSM must reside relatively close to the exploding WD. In that case the positive correlation of variable absorption with star forming galaxies is compatible with the CD scenario (Soker et al. 2013). We note though that presently the studies of Sternberg et al. (2011) and Maguire et al. (2013) cannot be used to distinguish between ISM and CSM features for an individual SN (Sternberg et al. 2014).

2.2. Massive hydrogen CSM

In the last decade more and more SNe Ia have been claimed to interact with a dense CSM (e.g., Silverman et al. 2013 and Fox et al. 2014). We mention here two such SN Ia, SN 2002ic and PTF 11kx. Hamuy et al. (2003) argued that the hydrogen lines in SN 2002ic can be explained by a few solar masses that have been lost by the progenitor shortly before the explosion, and attribute it to an AGB companion in the frame of the SD scenario. Livio & Riess (2003) attributed the massive CSM to the ejection of a CE, where a WD companion merged with the hot core of a massive AGB star; a process that was later termed the CD scenario. The massive CSM was very close, some mass as close as ~ 100 AU, to the SN origin when explosion occurred.

SN Ia PTF 11kx (Dilday et al. 2012) had narrow hydrogen lines and indications of interaction with a massive CSM which started 59 days after the explosion. Dilday et al. (2012) argued that the CSM was formed by a giant companion to the exploding WD, as is the case in some channels of the SD scenario. They dismiss the merger scenario as suggested by Livio & Riess (2003) on several grounds, e.g., it cannot account for several CSM shells. Soker et al. (2013) argued to the contrary, and explained PTF 11kx in the frame of the CD scenario. In particular, Soker et al. (2013) estimated the CSM mass within ~ 1000 AU to be $\gtrsim 0.2M_{\odot}$, much above what the SD scenario can supply.

Dilday et al. (2012) crudely estimate that the fraction of SNe Ia that exhibit prominent circumstellar interaction near maximum light, e.g., SN 2002ic and PTF 11kx, is $\sim 0.1 - 1\%$. As $\sim 1-2$ SN Ia occur per $1000M_{\odot}$ stars formed (Maoz et al. 2012), the estimate of Dilday et al. (2012) stands at $\sim 0.001 - 0.02$ SN Ia with massive CSM per $1000 M_{\odot}$ stars formed. The Monte Carlo simulations of Soker et al. (2013) show that the frequency of these systems is consistent with the CD scenario.

Rodney et al. (2014) take the SN Ia rate at short delay times of < 500 Myr (what they term prompt) to be constant. Based on that, we take the probability for explosion after the termination of the CE to be constant with time up to few $\times 10^5$ yrs. In our modelling this rate is higher than that found by Rodney et al. (2014). Namely, we find in this paper that the SN Ia rate within about one million years of the CE phase is very high. For a constant probability per unit time to explode within hundreds of thousands of years after merger, the probability to explode is linear with the radius of the CSM up to several pc, assuming the CSM expands with a constant velocity of tens of km s^{-1} . Namely, the probability for the system to explode by the time the CSM reached a radius of ~ 1 pc (as is the case for the Na absorbing gas,) is ~ 100 times that of a system where the CSM only reached a radius of ~ 0.01 pc, as is the case of the SN Ia-CSM systems. Therefore, the $0.1 - 1\%$ estimate by Dilday et al. (2012) for cases where the CSM is close to the exploding site, translates to few

10% of SNIPs (where the CSM is at ~ 1 pc). This is consistent with the estimate from the Na absorption lines discussed in Section 2.1.

3. SN REMNANTS Ia WITH CIRCUMSTELLAR MATTER

Out of a dozen of resolved SN Ia remnants, at least a few may be attributed to SN Ia that exploded inside a CSM shell. For Kepler’s SNR, the interaction of the SN Ia with the CSM is established (Patnaude et al. 2012). Our previous work on this SNR (Tsebrenko & Soker 2013) suggests that Kepler’s SN exploded inside a CSM shell that originated as a PN. We term this scenario SN Ia inside PN, or SNIP. In a recent work, we examined SNR G1.9+0.3 (Tsebrenko & Soker 2015) and suggested that its observed X-ray morphology also hints at a SNIP origin.

Examining the X-ray and radio SNR images in the Chandra SNR catalogue¹ (Seward et al. 2004), we try to identify other SNRs that might have evidence for SNIP origin. As an indication for a possible SNIP origin we take here the morphological feature of two opposite ‘ears’ in the SNR (nomenclature by Cassam-Chenaï et al. 2004), a feature both Kepler and G1.9+0.3 have. On the one hand some ‘ears’ might originate in ISM interaction rather than CSM. On the other hand some SNIPs might contain no ‘ears’ at all. As well, we don’t consider the possibility of forming the ears by jets blown by the merging WD and the core (see Tsebrenko & Soker 2013), although it exists. For the preliminary estimates of the present study we consider our approach to be adequate.

We focus only on close-by SNRs that have a significant apparent angular size, and are well-resolved to an extent that allows to identify or disprove the existence of two opposite ears in the SNR morphology. All of the SNe in our sample are dynamically young, with estimated ages of less than 10,000 yr (Borkowski et al. 2006; Caswell et al. 1982; Hendrick et al. 2003; Hughes et al. 1995; Park et al. 2007; Reynolds et al. 2008; Vink et al. 2006). In other words, we only examine SNRs Ia that have clearly resolved sharp images that can show relatively detailed filaments structure in the SNR shell. Very old SNRs that have been significantly influenced by ISM interaction are not considered. Though these criteria limit us to SNRs in our immediate neighborhood (the Galaxy and the Magellanic Clouds; MCs), we assume that this is a fair representative of other star-forming galaxies.

We have identified a total of 13 SNRs that comply with our criteria and list them in Table 2. In Kepler’s SNR and SNR G1.9+0.3, and possibly SNRs DEM L71, G299.2-2.9, 0534-69.9

¹<http://hea-www.cfa.harvard.edu/ChandraSNR/>

and 0519-69.0, we identify opposite ears structures. We define the opposite ears structure as two protrusions from the overall spherical shape of an SNR, directly opposite one to another. The protrusions have width of the order of roughly one tenth of the radius of the SNR so that they can be easily identified by eye. No other similar protrusions beside these two should be present for a positive identification. These SNRs are marked as having ears ("Yes") in Table 2. Some SNRs have such protrusions, but they are less proclaimed or the image is not sharp enough to determine if there are indeed opposite ears. These SNRs are marked as possibly having ears ("Maybe") in Table 2. We already performed hydrodynamical simulations to explain the first two SNRs as SNIPs. The study of SNR G299.2-2.9 is a goal of a future work.

From the listed SNRs Ia in the table we derive an initial estimate of $\sim 15 - 45\%$ of well-resolved SNRs Ia possessing the opposite-ears morphology. In estimating the SNIP fraction other uncertainties should be considered. First, other scenarios can also create opposite ears, lowering the number of SNIP out of the SNRs Ia having opposite ears. Such scenarios include dynamical interaction with the ISM, in which small randomly positioned protrusions can be created by instabilities in the ejecta (Warren & Blondin 2013), and jets blown during the merger process (Tsebrenko & Soker 2013). Another speculative possibility that we raise here is an asymmetric explosion with jets along a symmetry axis that can give rise to opposite Ears when the jets interact with the ISM.

We also note that detecting ears in SNRs can be a function of viewing angle. In Tsebrenko & Soker (2013) we estimated that the probability to observe the ears features in Kepler's SNR is roughly 40%. Therefore, some of the SNRs that we identified as not having ears in our sample might in fact be SNIPs, but with the ears projected in front and behind the SNR itself. This introduces an additional uncertainty to our crude estimate, lowering the number of SN Ia identified as SNIP candidates. Another source of uncertainties is the usage of an X-ray catalogue, that might be biased toward SNe Ia exploding in dense ISM and/or within a CSM. If a SN Ia occurs in a very low density ISM and there is no CSM, then the X-ray emission that results from the ejecta interaction with the surrounding gas will be very weak. We might miss non-interaction SN Ia. This is likely to be the case with SN Ia in the halo of the Galaxy. Overall the uncertainties are large, and our estimate of the fraction of SNIP candidates in well resolved SNRs Ia being approximately 15 – 45% is only a crude upper limit.

The resolved SNRs are all located in the star-forming Milky Way Galaxy and LMC. Graur & Maoz (2013) showed that star-forming galaxies have a mass-normalized SN Ia rate of $\simeq 0.118 \text{ SNum } (10^{-12} M_{\odot}^{-1} \text{ yr}^{-1})$, while passive galaxies (with no recent star formation) have a lower rate of $\simeq 0.082 \text{ SNum}$. Our proposed SNIP scenario is expected to occur in

systems that explode through the CD channel (see Section 1). This will predominantly occur in star-forming galaxies. Kelvin et al. (2014) show that $\simeq 34\%$ of the stellar mass in galaxies having a stellar mass of $M_* > 10^9 M_\odot$ in our local universe ($0.025 < z < 0.06$) resides within elliptical (passive) galaxies.

Assuming that no SNIPs occur in passive galaxies, and taking into account the mass-normalized SN Ia rates above (Graur & Maoz 2013), and the mass fraction in elliptical galaxies of 34%, we find that $\sim 75\%$ of SN Ia occur in star forming galaxies. With our estimate from Table 2 of 15–45% being SNIPs in star forming galaxies, we arrive to estimate that approximately 10–30% of all SNe Ia may be SNIPs by the opposite-ears criterion.

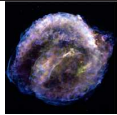
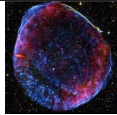
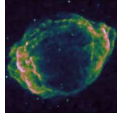
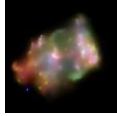
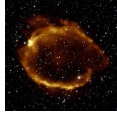
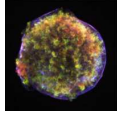
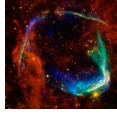
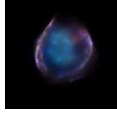
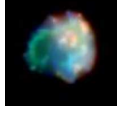
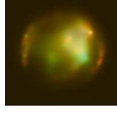
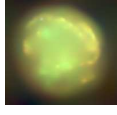


SNR	X-ray Image	Ears	SNR	X-ray Image	Ears
Kepler		Yes	1006		No
G1.9+0.3		Yes	3C 397		No
G299.2-2.9		Maybe	Tycho		No
RCW86		No	DEM L71		Maybe
N 103B		No	0548-70.4		No
0534-69.9		Maybe	0509-67.5		No
0519-69.0		Maybe	-	-	-

Table 2: Known well-resolved SNRs with ages less than 10,000 yrs. We identify the morphological feature of two opposite ears in between 2 and 6 of the 13 SNRs. All images are taken from the Chandra SNR Catalogue (references therein).

In the CD scenario the two WDs merge at the end of, or very shortly after, the CE

phase. In some cases the two WDs might not merge because the AGB envelope is not massive enough. The envelope is then ejected before merger. In such systems, according to the scenario discussed here, the two WDs mass is close or over the Chandrasekhar mass, and the PN contains "ears", i.e., small lobes. We are aware of two PNe that have been claimed to host such a WD binary system, and these indeed have "ears".

Nova V458 has a binary system at the center, with a very short orbital period of ~ 1.63 hr, consisting of a relatively massive WD ($M_1 \gtrsim 1.0M_\odot$) and a secondary post-AGB star ($M_2 \sim 0.6M_\odot$; Rodríguez-Gil et al. 2010). It is an elongated PN that has two opposite lobes (Corradi 2012; Wesson et al. 2008). The gravitational wave inspiral time for this binary is $\sim 4 \times 10^6$ yr, making it too long for a SNIP explosion to take place, but not by far.

PN G135.9+55.9 (TS01) hosts a binary system with an orbital period of ~ 3.92 hr and a total mass very close to the Chandrasekhar limit (Tovmassian et al. 2010). It is a PN that has two opposite ears (Richer et al. 2003; Stasińska et al. 2010).

These two systems, we argue, support our SNIP scenario. They belong to systems just outside the boundary of the parameter space of the CD scenario where merger has been barely prevented, most likely due to a too low AGB envelope mass. Many others WD-core systems with a total mass close to the Chandrasekhar mass merged at the end of the CE phase and formed SNIPs.

4. SUMMARY

In this work we estimated the fraction of SNe Ia exploding inside PNe (SNIPs), using three independent calculations. (i) An analysis of sodium absorption lines in SNRs Ia, based on Sternberg et al. (2014) and Maguire et al. (2013) and described in Section 2.1. The results suggest that $> 20\%$ of SN Ia possess massive CSM and thus can be potentially qualified as SNIPs. (ii) An estimation of the probability for SN Ia explosion that will have a massive hydrogen CSM, based on Dilday et al. (2012) and described in Section 2.2. This yields an estimate of $\sim \text{few} \times 10\%$ of all SNe Ia having SNIP origin. (iii) An examination of the X-ray morphologies of well-resolved close-by SNRs Ia, described in Section 3.

Approximately $15 - 45\%$ of the well-resolved SNRs Ia possess opposite ear-like features, which we take as evidence of SNIP origin. Considering the star-forming nature of the Galaxy and the LMC, and taking into account the mass-normalized SN Ia rates for star-forming and passive galaxies, this estimate translates to a fraction of $\sim 10 - 30\%$ of all SNe Ia having SNIP origin, as a crude upper limit.

It is not clear yet whether the core-degenerate (CD) scenario can account for all SN Ia and whether it can reproduce the DTD (for two opposite views see Ilkov & Soker 2013 and Mennekens et al. 2012). However, it seems quite secure that the CD scenario can explain the large fraction of SN Ia occurring shortly after star formation, i.e., within $t \lesssim 3 \times 10^8$ yr, i.e., shortly after the two massive stars of a binary system end their evolution on the AGB (Mennekens et al. 2012; Soker et al. 2013). Some studies argued for a very small contribution of the CD scenario. We attribute their results to two inaccurately treated processes. First is the mass transfer from the more massive star during its RGB and/or AGB phases to the still main-sequence companion. Soker et al. (2013) pointed out, based on the code used by García-Berro et al. (2012), that the transferred mass should be higher than usually assumed in population synthesis studies. The second inaccurately treated process is the CE ejection, which is too "optimistic" (in the sense that the common envelope is assumed to be easily ejected) in some population synthesis studies, e.g., Meng & Yang (2012).

We note that Maguire et al. (2013) argue that the CD scenario cannot account for the CSM they find in their study. We strongly disagree with that conclusion. Despite the difficulties and open questions listed in Table 1, we suggest that the CD scenario is the most likely scenario out of the 5 listed there to account for all the properties of the CSM (e.g., Soker et al. 2013; Tsebrenko & Soker 2013; Soker 2014; Tsebrenko & Soker 2015).

Our results, as well as other papers cited here, e.g., that the SD scenario contribution to SN Ia is at best very small, suggest that the focus in the open questions of SN Ia progenitors should be shifted from the SD scenario to other scenarios. Our view, as summarized in the last row of Table 1, is that the two main SN Ia channels are the DD and CD scenarios.

Though we could only propose crude estimates that still demand a deeper and more thorough analysis, we are confident in the conclusion that a significant fraction (at least 20%, and possibly more) of SNe Ia are SNIPs, most likely formed through the CD scenario.

We thank an anonymous referee for many detailed comments that substantially improved both the scientific content of the paper and the presentation of our results. This research was supported by the Asher Fund for Space Research at the Technion, and the E. and J. Bishop Research Fund at the Technion.

REFERENCES

- Aznar-Siguán, G., García-Berro, E., Lorén-Aguilar, P., José, J., & Isern, J. 2013, MNRAS, 434, 2539
- Bildsten, L., Shen, K. J., Weinberg, N. N., & Nelemans, G. 2007, ApJ, 662, L95

- Bloom, J. S., Kasen, D., Shen, K. J., et al. 2012, *ApJ*, 744, L17
- Borkowski, K. J., Williams, B. J., Reynolds, S. P., et al. 2006, *ApJ*, 642, L141
- Burkey, M. T., Reynolds, S. P., Borkowski, K. J., & Blondin, J. M. 2013, *ApJ*, 764, 63
- Cassam-Chenaï, G., Decourchelle, A., Ballet, J., et al. 2004, *A&A*, 414, 545
- Caswell, J. L., Haynes, R. F., Milne, D. K., & Wellington, K. J. 1982, *MNRAS*, 200, 1143
- Claeys, J. S. W., Pols, O. R., Izzard, R. G., Vink, J., & Verbunt, F. W. M. 2014, *A&A*, 563, A83
- Chugai, N. N. 2008, *Astronomy Letters*, 34, 389
- Corradi, R. L. M. 2012, *Mem. Soc. Astron. Italiana*, 83, 811
- Dilday, B., Howell, D. A., Cenko, S. B., et al. 2012, *Science*, 337, 942
- Di Stefano, R., Voss, R., & Claeys, J. S. W. 2011, *ApJ*, 738, LL1
- Fox, O. D., Silverman, J. M., Filippenko, A. V., et al. 2014, *arXiv:1408.6239*
- García-Berro, E., Lorén-Aguilar, P., Aznar-Siguán, G., et al. 2012, *ApJ*, 749, 25
- Graur, O., & Maoz, D. 2013, *MNRAS*, 430, 1746
- Guillochon, J., Dan, M., Ramirez-Ruiz, E., & Rosswog, S. 2010, *ApJ*, 709, L64
- Hachisu, I., Kato, M., & Nomoto, K. 2012, *ApJ*, 756, L4
- Hamers, A. S., Pols, O. R., Claeys, J. S. W., & Nelemans, G. 2013, *MNRAS*, 430, 2262
- Hamuy, M., Phillips, M. M., Suntzeff, N. B., et al. 2003, *Nature*, 424, 651
- Han, Z., & Podsiadlowski, P. 2004, *MNRAS*, 350, 1301
- Hendrick, S. P., Borkowski, K. J., & Reynolds, S. P. 2003, *ApJ*, 593, 370
- Hughes, J. P., Hayashi, I., Helfand, D., et al. 1995, *ApJ*, 444, L81
- Iben, I., Jr., & Tutukov, A. V. 1984, *ApJS*, 54, 335
- Ilkov, M., & Soker, N. 2012, *MNRAS*, 419, 1695
- Ilkov, M., & Soker, N. 2013, *MNRAS*, 428, 579

- Justham, S. 2011, *ApJ*, 730, LL34
- Kashi, A., & Soker, N. 2011, *MNRAS*, 417, 1466
- Katz, B., & Dong, S. 2012, *arXiv:1211.4584*
- Kelvin, L. S., Driver, S. P., Robotham, A. S. G., et al. 2014, *MNRAS*, 444, 1647
- Kerzendorf, W. E., Yong, D., Schmidt, B. P., et al. 2013, *ApJ*, 774, 99
- Kerzendorf, W. E., Childress, M., Scharwächter, J., Do, T., & Schmidt, B. P. 2014, *ApJ*, 782, 27
- Kozai, Y. 1962, *AJ*, 67, 591
- Kushnir, D., Katz, B., Dong, S., Livne, E., & Fernández, R. 2013, *arXiv:1303.1180*
- Levanon, N., Soker, N., & García-Berro, E. 2014, *arXiv:1408.1375*
- Lidov, M. L. 1962, *Planet. Space Sci.*, 9, 719
- Livio, M., & Riess, A. G. 2003, *ApJ*, 594, L93
- Livne, E., & Arnett, D. 1995, *ApJ*, 452, 62
- Lopez, L. A., Ramirez-Ruiz, E., Badenes, C., et al. 2009, *ApJ*, 706, L106
- Lorén-Aguilar, P., Isern, J., & García-Berro, E. 2010, *MNRAS*, 406, 2749
- Maguire, K., Sullivan, M., Patat, F., et al. 2013, *MNRAS*, 436, 222
- Maoz, D., Mannucci, F., & Brandt, T. D. 2012, *MNRAS*, 426, 3282
- Maoz, D., Mannucci, F., & Nelemans, G. 2014, *ARA&A*, 52, 107
- Meng, X., & Yang, W. 2012, *A&A*, 543, A137
- Mennekens, N., Vanbeveren, D., & De Greve, J. P. 2012, *arXiv:1212.0313*
- Nomoto, K. 1982, *ApJ*, 253, 798
- Nugent, P. E., Sullivan, M., Cenko, S. B., et al. 2011, *Nature*, 480, 344
- Park, S., Slane, P. O., Hughes, J. P., et al. 2007, *ApJ*, 665, 1173
- Pakmor, R., Kromer, M., Taubenberger, S., et al. 2012, *ApJ*, 747, L10

- Pakmor, R., Kromer, M., Taubenberger, S., & Springel, V. 2013, *ApJ*, 770, L8
- Papish, O., Soker, N., García-Berro, E., & Aznar-Siguán, G. 2015, submitted
- Patat, F., Chandra, P., Chevalier, R., et al. 2007, *Science*, 317, 924
- Patat, F., Chugai, N. N., Podsiadlowski, Ph., Mason, E., Melo, C., & Pasquini, L. 2011, *A&A*, 530, A63
- Patnaude, D. J., Badenes, C., Park, S., & Laming, J. M. 2012, *ApJ*, 756, 6
- Piersanti, L., Gagliardi, S., Iben, I., Jr., & Tornambé, A. 2003, *ApJ*, 583, 885
- Piersanti, L., Tornambé, A., Yungelson, L., & Straniero, O. 2013, *IAU Symposium*, 281, 209
- Piro, A. L., & Nakar, E. 2014, *ApJ*, 784, 85
- Prodan, S., Murray, N., & Thompson, T. A. 2013, arXiv:1305.2191
- Raskin, C., Scannapieco, E., Fryer, C., Rockefeller, G., & Timmes, F. X. 2012, *ApJ*, 746, 62
- Raskin, C., & Kasen, D. 2013, *ApJ*, 772, 1
- Raskin, C., Timmes, F. X., Scannapieco, E., Diehl, S., & Fryer, C. 2009, *MNRAS*, 399, L156
- Reynolds, S. P., Borkowski, K. J., Green, D. A., et al. 2008, *ApJ*, 680, L41
- Richer, M. G., López, J. A., Steffen, W., et al. 2003, *A&A*, 410, 911
- Rodney, S. A., Riess, A. G., Strolger, L.-G., et al. 2014, *AJ*, 148, 13
- Rodríguez-Gil, P., Santander-García, M., Knigge, C., et al. 2010, *MNRAS*, 407, L21
- Rosswog, S., Kasen, D., Guillochon, J., & Ramirez-Ruiz, E. 2009, *ApJ*, 705, L128
- Ruiter, A. J., Belczynski, K., Sim, S. A., Hillebrandt, W., Fryer, C. L., Fink, M., & Kromer, M. 2011, *MNRAS*, 417, 408
- Scalzo, R. A., Ruiter, A. J., & Sim, S. A. 2014, *MNRAS* (arXiv:1408.6601)
- Seitenzahl, I. R., Cescutti, G., Röpke, F. K., Ruiter, A. J., & Pakmor, R. 2013, *A&A*, 559, L5
- Seward, F., Smith, R., Hagler, J., et al. 2004, *Young Neutron Stars and Their Environments*, 218, 93

- Silverman, J. M., Nugent, P. E., Gal-Yam, A., et al. 2013, *ApJ*, 772, 125
- Shen, K. J., & Bildsten, L. 2009, *ApJ*, 699, 1365
- Shen, K. J., Guillochon, J., & Foley, R. J. 2013, *ApJ*, 770, L35
- Sparks, W. M., & Stecher, T. P. 1974, *ApJ*, 188, 149
- Soker, N. 2011, arXiv:1109.4652
- Soker, N. 2014, *MNRAS*, 444, L73
- Soker, N., Kashi, A., Garcia-Berro, E., Torres, S., & Camacho, J. 2013, *MNRAS*, 431, 1541
- Soker, N., García-Berro, E., & Althaus, L. G. 2014, *MNRAS*, 437, L66
- Stasińska, G., Morisset, C., Tovmassian, G., et al. 2010, *A&A*, 511, A44
- Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2014, *MNRAS*, 443, 1849
- Sternberg, A., Gal-Yam, A., Simon, J. D., et al. 2011, *Science*, 333, 856
- Thompson, T. A. 2011, *ApJ*, 741, 82
- Toonen, S., Nelemans, G., Bours, M., Portegies Zwart, S., Claeys, J., Mennekens, N., & Ruiter, A. 2013, *ASP Conference Proceedings*, Vol. 469. San Francisco: Astronomical Society of the Pacific., Edited by J. Krzesiński, G. Stachowski, P. Moskalik, and K. Bajan, p.329
- Tornambé, A., & Piersanti, L. 2013, *MNRAS*, 431, 1812
- Tovmassian, G., Yungelson, L., Rauch, T., et al. 2010, *ApJ*, 714, 178
- Tsebrenko, D., & Soker, N. 2013, *MNRAS*, 435, 320
- Tsebrenko, D., & Soker, N. 2015, submitted (arXiv:1407.6231)
- van Kerkwijk, M. H., Chang, P., & Justham, S. 2010, *ApJ*, 722, L157
- Vink, J., Bleeker, J., van der Heyden, K., et al. 2006, *ApJ*, 648, L33
- Warren, D. C., & Blondin, J. M. 2013, *MNRAS*, 429, 3099
- Webbink, R. F. 1984, *ApJ*, 277, 355
- Wesson, R., Barlow, M. J., Corradi, R. L. M., et al. 2008, *ApJ*, 688, L21

Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007

Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371